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Energy sustainability from analysis of sustainable development indicators: A case study in Taiwan

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ABSTRACT

As Taiwan has a dense population and only limited natural resources, the government began actively establishing a Taiwan's sustainable development indicators (TSDI) system in 2003, which was developed with reference to the Pressure–State Response (PSR) framework to evaluate the progress towards sustainability. Energy is a very important factor in leading to sustainable development at the national level. However, there are only two indicators concerning the energy sustainability in the TSDI system. This paper summarizes the current status of energy supply, energy consumption, carbon dioxide (CO_2) emissions and renewable energy production since the year 2000. The updated information on the TSDI was also addressed and analyzed to imply the progress towards energy sustainability during 2000–2008. Finally, the weighted-sum method was proposed to make an analysis of energy sustainability from Taiwan's renewable energy production, showing that this country has experienced a significant progress toward energy sustainability in recent years.

Contents

1. Introduction

Taiwan has a dense population and only limited natural resources. The energy consumption reached a total of 117.69 million kiloliters of oil equivalent (KLOE) in 2008, in contrast to 45.71 and 83.87 million KLOE in 1990 and 2000, respectively [1]. On average, the annual growth rate is about 5%. During the period, Taiwan's dependence on imported energy increased from 95.8% in 1990 to 99.3% in 2008. In recent years, the environmental issues such as global warming and sustainable development are consecutively arousing the concern of the public. Approximately in parallel with the energy consumption per capita, the per capita carbon dioxide (CO_2) emissions from the energy consumption remarkably increased in 18 years (i.e., from 5.5 metric tons per capita in 1990 to 12.1 metric tons per capita in 2008). In response to the Kyoto Protocol adopted in December 1997 and coming into effect in February 2005, Taiwan convened three National Energy Conferences in May 1998, June 2005 and April 2009, respectively. According to the Conferences, the most important conclusion was to create a new low-carbon economy and low-carbon society that balances economic development against environmental protection and energy security under the principles of "high efficiency", "high

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value-added", "low emission", and "low dependence (on foreign fuel sources)". For this reason, the energy strategies and policies for promoting energy saving and renewable energy in Taiwan have actively provided some environmental, financial, and economic incentives to pursue the energy sustainability [2,3].

To be in accordance with the trend of "Sustainable Development" first revealed by the World Commission on Environment and Development (WCSD) in 1987 [4], the issue of sustainable development has been a basic principle of national development in every country, even in every region or city. The 1992 Earth Summit held in Rio de Janeiro (Brazil) agreed to implement Agenda 21, which calls on countries to develop national-level sustainability indicators. In 2002, the World Summit on Sustainable Development (WSSD) held in Johannesburg (South Africa) produced the Sustainable Development Action Plan which placed on the agenda the concrete measures and goals for promoting energy sustainable development vital for the Millennium Development Goal [5]. The government consequently began to establish a Taiwan's sustainable development indicators (TSDI) system for evaluating the progress in promoting sustainable development. The National Council for Sustainable Development of Taiwan made joint efforts with the related ministries to actively establish the TSDI system since 1998. A set of 40 key indicators, which are most representative of sustainable development, were selected from 111 sustainability indicator candidates to form the TSDI system, which was developed with reference to the Pressure–State Response (PSR) framework of the United Nations Commission on Sustainable Development (USCSD). However, the indicators in the TSDI system concerning the energy sustainability are only CO_2 emissions per capita and energy intensity from the use of fossil fuels, and they do not contain other significant items related to renewable energy.

Energy plays a vital role in the economic development and social/national security. However, current patterns of energy supply and energy use are unsustainable because the environmental issues such as global warming and acid rain arise from the energy consumption. In order to complement Chapter 40 of the Agenda 21 and the USCSD, the International Atomic Energy Agency (IAEA) and several international organizations cooperated to establish the Indicators for Sustainable Energy Development (ISED) in 1999 [5]. In 2005, the energy indicators for sustainable development (EISD) were formally developed by five major international organizations. The EISD is comprised of 30 indicators, which are classified into social, economic and environmental dimensions. The set of energy indicators of economic dimension consists of 16 indicators, including energy intensities in various sectors and renewable energy share. In the environmental dimension, the indicator of greenhouse gases (GHG) emissions from energy use per capita and per unit of grass domestic product (GDP) is included in correlation with the climate change.

Since late 1990s, the Cabinet of Taiwan has actively promoted the renewable energy development and upgraded the efficiency of energy use. In this study, the statistic documents published by the Taiwan central government were utilized to provide a systemic and analytical description about the trends of energy sustainability between 2000 and 2008. The main subjects covered in this paper were described in the following key elements:

- Analysis of energy supply, consumption and carbon dioxide (CO_2) emissions.
- Current status of installed generation from renewable energy sources.
- Taiwan sustainable development indicator (TSDI) system.
- Analysis of energy sustainability from TSDI system.
- An analysis of energy sustainability from Taiwan's renewable energy production.

2. Analysis of energy supply, consumption and carbon dioxide (CO_2) emissions

2.1. Current status of energy supply

With the increase in the economic development and living level during the past decades, the total amount of energy supply in Taiwan increased from 58.74 million KLOE in 1990, 104.46 million KLOE in 2000, to 142.5 million KLOE in 2008 (listed in Table 1). On average, the annual growth rate is 5.05% [1]. Due to the energy policy on the energy saving and renewable energy development, the annual growth rate of energy supply was falling during the two periods: 7.30% from 1990 to 2000, and 3.88% from 2000 to 2008. It should be noted that the energy supply decreased from 147.24 million KLOE in 2007 to 142.47 million KLOE in 2008. The decrease in the energy demand was mainly caused by the financial crisis. As listed in Table 2, the ratio of indigenous energy to total energy supply (i.e., dependence on imported energy) significantly decreased from 1.32% in 2000, to 0.78% in 2008 because land-based fossil energy resources (i.e., coal and natural gas) of Taiwan were gradually exhausted during that period. To promote the development and application of renewable energy, the government of Taiwan, under the planning and execution of the Bureau of Energy (BOE) of the Ministry of Economic Affairs (MOEA), has implemented many financial measures for subsidizing the solar photovoltaic energy and wind power since 2000 [2,3]. Therefore, the energy supply from solar photovoltaic & wind power remarkably increased from 0.1×10^3 KLOE in 2000 to 56.7×10^3 KLOE in 2008 [1].

Table 1
Energy, economic and environmental situations of Taiwan since 2000.[a]

Year	Mid-year population (10^3 capita)	Total energy supply[b] (10^6 KLOE)	Total final consumption[c] (10^6 KLOE)	Total domestic consumption[d] (10^6 KLOE)	GDP (US$ million at current prices)	Garbage generated (metric ton)	Garbage incinerated (metric ton)
2000	22,125	104.46	84.17	93.19	321,230	8,729,502	2,659,652
2001	22,278	109.10	88.98	98.74	291,694	8,334,407	3,922,387
2002	22,397	114.36	92.42	101.80	297,668	7,984,837	5,311,000
2003	22,494	122.64	95.80	105.48	305,624	7,708,019	5,470,736
2004	22,575	135.71	100.05	110.03	331,007	7,714,959	5,611,505
2005	22,652	136.96	102.23	112.61	355,958	7,828,685	5,614,930
2006	22,740	139.91	104.70	115.40	366,357	7,791,606	5,683,033
2007	22,828	147.24	110.68	121.21	384,768	7,949,448	5,948,765
2008	22,904	142.47	108.44	117.69	391,278	7,537,377	6,110,838

[a] Source [1].
[b] Total primary energy supply = production + imports + exports + bunkers ± stock change.
[c] The value, taken as the unit of 10^6 KLOE (kiloliters of oil equivalent), was obtained by the summation of energy consumption from the industrial, transportation, agricultural, service, residential and non-energy use sectors.
[d] Total domestic consumption = total final consumption + energy sector own use.

Table 2
Status of energy and environment indicators of Taiwan since 2000.[a].

Year	Mid-year population (10^3 capita)	Total final consumption[b] (10^6 KLOE)	CO_2 emission per capita per year[c] (MT/capita-year)	Garbage generated per capita per day (kg/capita-day)	Energy use intensity (LOE/10^3 NT$)	Dependence[d] (%)
2000	22,125	84.17	9.67	1.091	9.26	98.68
2001	22,278	88.98	9.80	1.031	10.00	98.61
2002	22,397	92.42	10.12	0.982	9.84	98.81
2003	22,494	95.80	10.52	0.941	9.86	98.88
2004	22,575	100.05	11.00	0.932	9.69	98.99
2005	22,652	102.23	11.32	0.945	9.53	99.11
2006	22,740	104.70	11.62	0.936	9.31	99.18
2007	22,828	110.68	11.73	0.951	9.25	99.22
2008	22,904	108.44	11.17	0.896	8.98	99.23

[a] Sources [1,6].
[b] The value was taken as the unit of 10^6 KLOE (kiloliters of oil equivalent).
[c] The CO_2 emission value was calculated from final energy consumption using the sector approach.
[d] Defined as the dependence on imported energy.

During the period from 1990 to 2008, the structure of energy supply in Taiwan has allocated and changed as follows:

- Coal and coal products increased from 14.02×10^6 KLOE (23.87%) in 1990 to 46.19×10^6 KLOE (32.42%) in 2008.
- Crude oil and petroleum products increased from 32.32×10^6 KLOE in 1990 to 70.47×10^6 KLOE in 2008, while the corresponding percentage slightly decreased from 55.02% in 1990 to 49.46% in 2008.
- Natural gas (including imported liquefied natural gas) significantly increased 2.25×10^6 KLOE (3.82%) in 1990 to 13.42×10^6 KLOE (9.42%) in 2008.
- Conventional hydropower reflected the trend of stable supply on an average of 416×10^3 KLOE. However, the percentage decreased from 1.04% in 1990 to 0.29% in 2008.
- Nuclear power slightly increased from 9.52×10^6 KLOE in 1990 to 11.82×10^6 KLOE in 2008, while the corresponding percentage decreased from 16.20% in 1990 to 8.30% in 2008.
- The percentage of solar photovoltaic & wind power increased from 0.00% in 1990 to 56.7×10^3 KLOE (0.04%) in 2008.
- Solar thermal energy increased from 19.6×10^3 KLOE (0.03%) in 1990 to 109.5×10^3 KLOE (0.08%) in 2008.

2.2. Current status of energy consumption

In proportion to the energy supply described above, the domestic energy consumption in Taiwan significantly increased from 51.91 million KLOE in 1990, 93.19 million KLOE in 2000, to 117.69 million KLOE in 2008. According to the data in 2008, 97.71% was used in energy, and 2.29% was used in non-energy. Table 1 also showed a proportional trend of the final energy consumption. The average annual growth rate of domestic energy consumption was 4.65% [1], which was close to the average annual growth rate (i.e., 4.93%) of gross national product (GNP) during the period. On the other hand, the quantity of municipal solid waste (MSW) generated in Taiwan has increased to the level of the years from 1997 to 1998 and then decreased [2,6]. The quantity of MSW from the energy consumption and economic development has been decoupled because Taiwan's Environmental Protection Administrations (EPA), the primary central government-level agency responsible for environmental issues, began to promulgate stringent regulation to establish an integrated MSW reduction program and resource recycling system in 1990s, resulting in the gradual reduction of MSW generated, collected and thereafter treated. For example, the generated quantities of MSW were about 7.24, 9.20, 8.73, and 7.54 million metric tons in 1991, 1997, 2000 and 2008, respectively.

According to the energy form and sector, the structure of domestic energy consumption in Taiwan has changed during the period from 2000 to 2008 as follows:

- Classified by the energy form, the domestic energy consumption has been allocated as follows: 60.05 million KLOE (51.03%) for electricity, 45.53 million KLOE (38.68%) for petroleum products, 9.06 million KLOE (7.69%) for coal & coal products, 2.78 million KLOE (2.36%) for natural gas, and 0.27 million KLOE (0.23%) for other forms (i.e., solar thermal and heat) in 2008, as compared to 23.98 million KLOE (46.19%) for petroleum products, 21.69 million KLOE (41.79%) for electricity, 4.65 million KLOE (9.50%) for coal & coal products, 1.11 million KLOE (2.27%) for natural gas, and 0.015 million KLOE (0.03%) for other forms (i.e., solar thermal) in 2000.
- Classified by the sector, the domestic energy consumption has been allocated as follows: 61.88 million KLOE (52.58%) for the industrial sector, 15.05 million KLOE (12.79%) for the transportation sector, 13.78 million KLOE (11.71%) for the commercial (services) sector, 13.57 million KLOE (11.53%) for the residential sector, 9.54 million KLOE (8.10%) for the energy sector (own use), 2.70 million KLOE (2.29%) for the non-energy use sector, and 1.17 million KLOE (0.99%) for the agricultural sector in 2008, as compared to 24.42 million KLOE (47.93%) for the industrial sector, 8.01 million KLOE (15.43%) for the transportation sector, 6.01 million KLOE (11.58%) for the residential sector, 4.99 million KLOE (9.62%) for the services sector, 4.99 million KLOE (9.61%) for the energy sector (own use), 2.02 million KLOE (3.89%) for the non-energy use sector, and 1.46 million KLOE (2.81%) for the agricultural sector in 2000.

2.3. Current status of carbon dioxide (CO_2) emissions

It is well known that the main anthropogenic greenhouse gas (GHG) is carbon dioxide (CO_2) because it is closely related to the widespread use of the fossil energy. The considerable increase in the atmospheric concentration could be expected to trigger global warming and cause adverse environmental disasters. CO_2 emissions from the combustion of fossil fuels such as coal, petroleum and natural gas are the most important sources of anthropogenic GHG emissions all over the industrialized countries. With respect to the national inventories of CO_2 emissions from anthropogenic sources in Taiwan, the Taiwanese Environmental Protection Administration (EPA) first issued the report regarding the United Nations' Framework Convention on Climate Change (UNFCCC) National Communication of Taiwan in 2000 [7]. It was summarized that the total of CO_2 emissions without land-use change and forestry (LUCF) in Taiwan area was over 200 million metric tons in

2000. The largest source of CO_2 emissions was from the energy sector (combustion of fossil fuels) while the next important source was from the sector of industrial processes.

The Reference Approach of the Intergovernmental Panel on Climate Change (IPCC) method is easily available to estimate CO_2 emissions from fossil fuel consumption. This reference method first estimates "apparent consumption" of fossil fuels using national energy statistics according to the International Energy Agency (IEA) reporting form. Thus, apparent consumptions of primary fuels (including coals, crude oil, natural gas, and natural gas liquids) can be obtained by subtracting the consumption of non-energy use from the domestic energy consumption. Next, apparent consumptions of primary fuels needed to be converted to a common energy unit (e.g., TJ) using a conversion factor (i.e., 1 l of oil equivalent = 9000 kcal = 37,674 J). Once apparent consumption represented by energy unit was estimated, the coming calculation was made using effective fuel-specific CO_2 emission factor (kg/TJ). Table 2 also summarized the results in estimating CO_2 emissions per capita from the combustion of fossil fuels in Taiwan during the period of 2000–2008. It showed that the CO_2 emissions from the combustion of fuels slightly increased from 214.25 million metric tons in 2000 to 256.97 million metric tons in 2008. On average, the CO_2 emissions from the combustion of fuels annually increased by only 2.30%, showing that the governmental promotion of GHG emissions mitigation has obtained significant benefits in recent years. The analysis reveals that the CO_2 emission per capita in Taiwan area was on the increasing trend in proportion to the increase in the domestic energy consumption: 9.67 metric tons per capita in 2000, and 11.73 metric tons per capita in 2007. As analyzed in the energy supply and energy consumption, the CO_2 emission per capita in 2008 (i.e., 11.17 metric tons per capita) was lower than that in 2007 due to financial crisis. On average, CO_2 emission per capita increased annually by 1.82% during the period of 2000–2008.

3. Current status of installed generation from renewable energy sources

In response to the Kyoto Protocol adopted in December 1997 and the era of high fossil energy prices, promoting the utilization of renewable energy has been considered as one of the most environment-friendly strategies for the purpose of getting an equal focus on economic development, energy security, and environmental protection. In January 2002, the Executive Yuan of Taiwan adopted the "Renewable Energy Development Plan". The Council for Economic Planning and Development (CEPD) was in charge of coordinating the efforts from central government authorities in promoting renewable energy. The important measures and promotions in the Plan were summarized in the previous study [2].

Generally, renewable energy includes wind energy, solar energy, biomass energy, hydro energy, and geothermal energy. However, due to its geographical features, Taiwan has substantial reserves of renewable energy sources, especially in biomass, solar, and wind resources. By December of 2007, the total installed capacity of renewable power generation reached 2843 MW [8], which produced approximately 7.65 billion kW-h of electricity annually. This amount of electricity from renewable energy sources can provide an annual electricity consumption of 1.91 million for households. As listed in Table 3 [1,6], the energy supply from renewable energy sources during the period of 2000–2008 to 2008 was further analyzed as follows:

- Conventional hydropower

  Conventional hydropower is one kind of renewable energy, but the negative impacts on the environment systems is still under debate. In order to reduce the impact on rivers, the small hydropower facilities have been mainly developed. In recent years, the total installed capacity (about 1922 MW) of hydropower showed stability due to the difficulty of the large-scale hydropower exploitation in Taiwan.
- Biomass energy

  Regarding the development of the stationary biopower system, currently a total installed capacity of 772 MW for power generation has been achieved through biomass energy utilization, which is primarily based on MSW incineration generation (622.5 MW), biogas power generation (24.5 MW), and the utilization of agricultural and industrial wastes such as paper mill waste, bagasse and rice straw (125 MW). More than 90% of this biopower, however, was substantially supplied by 24 operational large incineration plants feeding MSW, agricultural wastes and general industrial wastes. In early 1990s, the central competent authority (i.e., EPA) of Taiwan has adopted a strategy favoring the treatment of MSW incineration. As a result, the electric power generation from MSW incineration plants increased from 1117.0 million kW-h (equivalent to 106.8×10^3 KLOE based on the conversion factor of 37.656 MJ/LOE) in 2000 to 2967.2 million kW-h (equivalent to 283.7×10^3 KLOE) in 2008.
- Solar energy

  Taiwan, which lies in a sub-tropical zone between 21°N and 25°N latitudes, provides the most excellent solar irradiation for water heating and photovoltaic applications. Under the encouragement from the government in recent years, the accumulated installation area of heat collectors in Taiwan has reached 1 million m^2 for solar water heaters since 2000. In 2008, the installation of solar water heater systems in 0.44 million households has reached around 1.78 million m^2, which is equivalently close to an annual energy saving of about 110.0×10^3 KLOE of traditional fossil fuels, For photovoltaic

Table 3
Status of renewable energy supply and biopower generation of Taiwan since 2000.[a]

Year	Conventional hydropower (10^3 KLOE)	Solar photovoltaic & wind power (10^3 KLOE)	Solar thermal energy (10^3 KLOE)	Biopower[b]		Sum (10^3 KLOE)
				(10^3 kW-h)	(10^3 KLOE)	
2000	436.7	0.1	77.3	1,117,023	106.8	620.9
2001	487.5	0.8	81.1	1,662,327	158.9	728.3
2002	266.5	0.8	84.3	2,503,212	239.3	590.9
2003	290.2	2.3	87.9	2,616,001	250.1	630.5
2004	306.9	2.5	92.7	2,769,921	264.8	666.9
2005	381.1	8.8	97.5	2,852,242	272.7	760.1
2006	390.8	26.7	102.4	2,856,682	273.1	793.0
2007	422.3	42.6	105.5	2,960,269	283.0	853.4
2008	411.6	56.7	109.5	2,967,218	283.7	861.5

[a] Source [1].
[b] Electricity power was substantially generated from 24 large MSW incineration plants [6].

(PV) demonstration systems, the total capacity whose subsidization had been approved of was about 530 kW during the period of 1990–2001. In order to further facilitate renewable energy utilization from solar energy, the relevant promotion regulation ("*Assistance Regulations Governing Demonstration System Installation for Electricity Generation from Solar Photovoltaics*") was first issued in March 2002. The total installed capacity of photovoltaic (PV) demonstration systems approved under the subsidization from the central competent authority (i.e., MOEA) has been up to about 4.1 MW by 2008.

- Wind energy

  To develop wind energy, Taiwan has an enormous advantage in that it is excellent in geographic location and has abundant wind resources along the western and southern coasts and on offshore island. Under the funding support of the central competent authority (i.e., MOEA) since 2000, the subsidization of three wind power demonstration systems had gained approval by the end of 2002. The three systems include 2.64 MW Mai-Liao system (Yunlin County) in 2000, 2.4 MW Chung-Tun system (Penghu County) in 2001 and 3.5 MW Chu-Pei (Hsinchu County) in 2002. Since then, the state-owned enterprise (i.e., Taiwan Power Co.) and private enterprises have heavily invested in the wind power plants under the policy supports, assistance incentives and economic considerations. The total installed capacity of wind power demonstration systems whose subsidization was approved of by 2008 was around 358 MW with 190 sets of wind turbines built by the state-owned company and some private sectors. Assuming that 1 kW of the installed capacity averagely produces 2700 kW-h annually, wind power can generate a total of 967 million kW-h annually.

4. Taiwan sustainable development indicator (TSDI) system

In early 1990s, the environmental issue known as global warming arose from the enormous use of energy/electricity because it was closely related to the GHG emissions. In view of the fact that the sustainable development arose from the global warming, the Executive Yuan (Cabinet) of Taiwan set up an inter-ministerial task force ("The Executive Yuan's Special Task Force on Global Environmental Changes") in May 1992, and reorganized it into the "Committee on Global Change Policy" in August 1994. Later, in order to fulfill the obligation to protect the global environment and incorporate sustainable development concepts into the governmental regulations, the Executive Yuan of Taiwan established the National Council for Sustainable Development (NCSD) in August 1997. Under the organization structure of the NCSD, the Premier acts as Chairman of the Council in order to provide concrete policies and measures for promoting sustainable development. Also, the NCSD has set up nine working groups to promote and coordinate sustainable development issues, including energy saving-carbon reduction and climate change, land resources, biodiversity, energy & production, transportation & life, technology & evaluation, urban & rural development, health & welfare, and education & promotion.

To be in accordance with the concept of "Sustainable Development" revealed by the World Commission on Environment and Development (WCSD) in 1987, and to be in response to the mandate (i.e., Chapter 40 of Agenda 21) granted by the United Nations Commission on Sustainable Development (UNCSD), the NCSD has made great efforts to use an effective means for recognizing the social, economic and environmental situations of Taiwan and measuring progress on sustainable development at the national level. In its efforts to achieve this goal for developing a set of national sustainable development indicators (SDI), the relevant working groups under the NCSD have reviewed 111 sustainability indicators since 1998. Based on the feasibility and stability of statistic data collection, the significance of correlation with public policy, the possibility of international collaboration, and other considerations, the NCSD finally selected a set of 40 meaningful and representative indicators for assessing sustainable development and creating the system of SDI for Taiwan in 2003. Basically, the TSDI system was developed with reference to the UN's Pressure–State Response (PSR) framework as well as Taiwan's current development status. These core indicators are categorized into six dimensions (shown in Fig. 1), which include the respective indicators as follows.

- Social pressure: Amount of solid waste produced per person per day, area of betel nuts plantation, number of accepted pollution complaints, death rate of cancer, epidemic infection rate, and unemployment rate.
- Economic pressure: Computer per family, cement production per capita, ratio of pesticide consumption to agricultural production, ratio of industrial water consumption to industrial production value, ratio of resource-consuming industrial production value to manufacturing production value, labor productivity index of manufacturing, and energy use intensity.
- Environmental quality: The emission amount of carbon dioxide (CO_2) per capita, average pollutant standards index (PSI), light-polluted streams percentage, reservoir water quality, percentage of waste recycling and reuse, and growth rate of low-level radioactive solid wastes
- Ecological resources: Ratio of areas depleted of natural resources, ratio of natural coastline, ratio of healthy forest, percentage of arable land, effort of fisheries yield per unit, ratio of protected area, and supply of water resources.

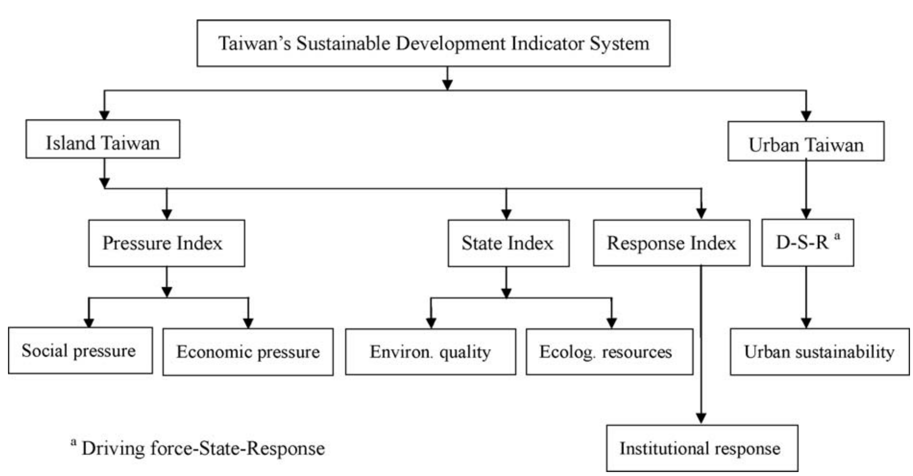


Fig. 1. The dimensions of Taiwan's sustainable development indicators (TSDI) system.

- Institutional response: Ratio of the environmental budget to the total government budget, government tax incentives to pollution prevention and resource recycling, ratio of the completed environmental impact assessment (EIA) reviews, ratio of wastewater treatment, number of legally banned or strictly regulated chemicals, number of eco-labeling in use, and extent of cooperation between government and environmental NGOs.
- Sustainable urban development: Per capita urban income, car ownership, number of transit passenger, increase rate of urban area, metropolitan air pollution, park area per person, and ratio of polluted stream length.

According to the Annual Reports on National Sustainable Development [9], a composite analysis of the state, pressure and response domains showed that the state of the ecology and environment has experienced an overall deviation away from sustainability, due to the greater load of ecological resources in recent years despite improvements in environmental pollution (quality). In terms of pressure domain, there is a growing gap between social and economic development, reflecting a transformation in Taiwan's economic structure over the past decade. On the other hand, the response domain showed the government's determination to implement policies that promote sustainable development. The sustainable development trends in the six dimensions during the period of 1988–2007 are further summarized as follows:

- Ecological resources

  Composite index scores of ecological resources showed a downward trend during the period of 1988–2077, indicating that the status of ecological resources in Taiwan has deviated away from sustainability for the past two decades. On the basis of the data in 2006 and 2007, aside from the values for the ratio of healthy forest (i.e., undamaged forest area), all other indicator values in 2007 were lower than those in 2006. As a result, the composite index score in 2007 was higher than that in 2006, showing a progress toward sustainability.
- Environmental quality

  Composite index scores of environmental quality (or environmental pollution) have progressed towards sustainability since 2004, exhibiting a positive change in overall environmental quality during the period of 2004–2007. As the trend of each indicator showed, continual promotion of national garbage resource recycling has brought about a steady improvement in the values for the rate indicator of waste resource recycling since 1998. On the other hand, the CO_2 emissions indicator has steadily declined during the period. However, the score of this indicator in 2008 was larger than that in 2007.
- Social pressure

  Composite index scores of social pressure continually dropped during the period of 1988–1997, representing a divergence away from sustainability. Since then, the slightly increased index scores reflect the stable sustainability of society in Taiwan. As described above, the daily per capita garbage generated has significantly decreased due to the waste management policy for MSW recycling since 1997. As listed in Table 2, the daily per capita garbage volume is only 0.895 kg/capita-day in 2008 as compared to 1.143 kg/capita-day in 1997. Also, betel nut plantation area has gradually decreased since 1999. Other indicators in the social pressure dimension, however, have increased.
- Economic pressure

  The composite index score exceeded the base mark in 1988, and now has reached the 2007 score of 107.97. The dimension shows a declining trend in overall economic pressure, and advances toward sustainable development. As individual indicators show, the average per capita production of cement has continued to decrease while the computer per family, the efficiency of water usage in manufacture, labor productivity index of manufacturing, and energy use intensity have increased in recent years. However, pesticide consumption and the ratios of value in total production output by resource-intensive industries still continue to rise.
- Institutional response

  Overall, the composite index scores have been above the baseline of 100.0 and indicate a continuing trend of sustainability during the past two decades. This situation was closely related to the governmental, corporate, and civil efforts to implement environmental regulations and institutional systems. However, the institutional system indicators remained steady during the period of 2005–2007.
- Sustainable urban development

  General speaking, Taiwan's urban sustainability composite index scores are on the rise in recent years. It can be expected that the number of transit passengers will be on the significant increase because the mass rapid transit (MRT) and high-speed railway systems will be completed during the period. On the other hand, the park area per person is gradually available and the annual rate of serious air pollution in urban areas has remarkably improved. As demonstrated [10], the urban development in Taiwan was recently analyzed using a sensitivity model based on the sustainability indicators.

5. Analysis of energy sustainability from TSDI system

Energy plays an essential role in achieving sustainable development because it is significantly correlated with the social, economic and environmental development. In 1992, the Earth Summit concluded that adequate indicators help countries and regions to make informed decisions concerning sustainable development. In other words, indicators can give an overview of progress towards energy, environmental and economic trends concerning sustainability domain at the national level. Consequently, energy indicators will be useful for monitoring progress towards sustainability, and also for communicating energy and related issues to the policy-makers and the public in order to facilitate institutional dialogue [5].

Among international communities, many indicator systems are currently used for the sustainable development based on their usages and features of calculation methods [4]. As reviewed by Patlitzianas et al. [11], several kinds of energy indicators have been developed. For the purpose of pursuing energy sustainability, the energy indicators for sustainable development (EISD), which can be used as an analytical tool for energy decision-makers and policy-makers, was developed by the International Atomic Energy Agency (IAEA), the United Nations Department of Economic and Social Affairs (UNDESA), the International Energy Agency (IEA), the European Environment Agency (EEA), and the Statistical Office of the European Communities (EUROSTAT) [11–13]. In the EISD, there are 30 indicators classified into social, economic and environmental dimensions [5]. The three dimensions are further separated in sections in accordance with the objectivity & health, the energy use & energy security, and atmospheric, and aquatic & land situation, respectively. The EISD set has been applied to the analysis of the energy sectors in the Baltic countries using ten indicators related to energy and environment [14].

The comparison between the TSDI and EISD shows that only two indicators (i.e., energy use intensity and CO_2 emissions per capita) in the former are included in the latter. The selected TSDI and their relationships with energy sustainability are listed in

Table 4
TSDI selected for the energy sustainability.

Index type	Dimension	Indicator	Relationship with sustainability
Pressure	Economic	Energy use intensity (GDP per unit of total energy consumption)	The decrease in density of energy utilization implies an increase in efficiency of energy use, which is a step towards sustainable development due to a decrease in the use of fossil fuels with increasing gross domestic product (GDP) simultaneously.
State	Environmental	Carbon dioxide generation per capita	Carbon dioxide (CO_2) is one of the greenhouse gases, which are closely related to the combustion use of fossil fuels (i.e., the energy sector) and climate change (global warming). The decrease in the emission amount of CO_2 is the goal of sustainable development.

Table 4. Nowadays, sustainable energy development should balance the objectives of energy security against economic development and environment protection. As a result, the sustainable energy policies in Taiwan should focus on the efficient use of limited energy resources, the development of clean energy, and the security (or diversification) of energy supply. On the basis of the data listed in Table 2, the TSDI concerning energy sustainability during the period of 2000–2008 were further discussed as follows:

- Energy use intensity

  The energy intensity or energy use intensity is usually defined as a measurement of the energy efficiency in producing a given level of output or activity. The indicator, a marker of aggregate energy intensity of the economy, is commonly considered as units of energy per unit GNP. Trends in the energy intensity indicator indicate the general relationship of energy consumption to economic development and provide a rough basis for projecting energy consumption and its environmental impacts (i.e., GHG emissions and air pollution emissions). The data in Table 2 reveal that the indicator has reduced from the maximum value 10.00 LOE per thousand NT dollars in 2001 to 8.98 LOE per thousand NT dollars in 2008. On average, the energy use improves by 1.54% annually. It represents an aggregate of energy consumption linking to the improvement in energy efficiency of the manufacturing, transportation, commercial/services and residential sectors. This indicator in Taiwan has positive trends towards the savings of primary energy supply and energy savings in the sectors, indicating that the implementing agencies at all levels and the public and private sectors are making continual efforts to progress towards energy sustainability.
- CO_2 emissions per capita

  Carbon dioxide (CO_2) is the most important greenhouse gas mainly produced by human activities such as burning fossil fuels, which is implicated in global warming. As listed in Table 2, the CO_2 emissions per capita in Taiwan have showed a rising trend but its growth rate has been falling in recent years. However, the indicator first dropped from 11.73 MT/capita in 2007 to 11.17 MT/capita in 2008, reflecting that the CO_2 emission in 2008 was 256.97 million metric tons in contrast to 268.88 million metric tons in 2007 [9]. On average, annual growth rate was 4.80% during the period of 1990–2008, which could be divided into two development stages: 6.85% from 1990 to 2001, and 2.30% from 2001 to 2008. This indicator seemed to be on the increasing trend, indicating an overall deviation away from energy sustainability. However, the decoupling of economic development from energy consumption has markedly approached toward sustainability in recent years.

6. An analysis of energy sustainability from Taiwan's renewable energy production

In response to the era of high prices of fossil energy and global trend towards greenhouse gas emissions mitigation, promoting the energy utilization from renewable sources is considered as a critical strategy internationally. As a result, the diversification of energy supply from renewable energy has been selected as a vital indicator in the EISD and other sustainability indicator systems (e.g., Environmental Sustainability Index) because it can provide the information about clean (non-carbon) energy in electricity generation and generating capacity. From the viewpoint of evaluating Taiwan's progress in promoting environmental management and energy sustainability, the renewable energy supplied as electricity form should be selected as an indicator in the economic pressure domain of the TSDI system [15].

According to the data (Table 3) concerning the renewable energy supply and biopower generation in Taiwan since 2000 (as the base year), the renewable energy indicator is calculated as follows.

For one renewable energy (j fixed), the ratio (i.e., R) of the current year data (i.e., $E_{i+1,j}$) to the former year data (i.e., $E_{i,j}$):

$$R_{i,j} = 100 \times \frac{E_{i+1,j}}{E_{i,j}}$$

Table 5
The indicator scores from renewable energy supply and biopower generation of Taiwan since 2000.[a]

Year	Conventional hydropower		Solar photovoltaic and wind power		Solar thermal energy		Biopower[b]		Score	
	W	R	W	R	W	R	W	R	$\Sigma(R \times W)$	Increment
2000	0.7033	100.0	0.0002	100.0	0.1245	100.0	0.1720	100.0	100.0	(base year)
2001	0.6694	116.3	0.0011	800.0	0.1114	104.9	0.2182	148.8	122.9	+22.9
2002	0.4510	54.7	0.0014	100.0	0.1427	103.9	0.4050	150.6	123.5	+0.6
2003	0.4603	108.9	0.0036	287.5	0.1394	104.3	0.3967	104.5	130.7	+7.2
2004	0.4602	105.8	0.0037	108.7	0.1390	105.5	0.3971	105.9	136.5	+5.8
2005	0.5014	91.6	0.0116	352.0	0.1283	105.2	0.3588	103.0	137.0	+0.5
2006	0.4928	102.5	0.0337	303.4	0.1291	105.0	0.3444	100.1	145.8	+8.8
2007	0.4948	108.1	0.0499	159.6	0.1236	103.0	0.3316	103.6	154.3	+8.5
2008	0.4778	97.5	0.0658	133.1	0.1271	103.8	0.3293	100.2	155.8	+1.5

[a] Source [1].
[b] Electricity power was substantially generated from 24 large MSW incineration plants [6].

where i = 1,2, . . ., and 9 for the years of 2000, 2001, . . . and 2008, respectively, j = 1, 2, 3, and 4 for the sources of hydropower, solar PV/wind power, solar thermal power, and biopower, respectively.

For 1 year (i fixed), the weighting (i.e., W) of one renewable energy (i.e., $E_{i,j}$) relative to the summation of all renewable energy sources (i.e., $\Sigma E_{i,j}$):

$$W_{i,j} = \frac{E_{i,j}}{\sum(E_{i,j})}$$

The score of 1 year (i fixed) for sustainability (i.e., S_i) from renewable energy sources can be thus calculated using the weighted-sum method.

$$S_i = \sum(R_{i,j} \times W_{i,j})$$

The indicator scores during the period of 2001–2008 have been obtained and listed in Table 5, showing that the state of renewable energy development has experienced a significant progress toward energy sustainability in recent years. This trend is positive mainly due to the Taiwan government's efforts and determination to implement policies that promote renewable energy as described in Section 3.

7. Conclusions and prospects

Since the Rio Declaration from the Earth Summit in 1992, the energy policies relating to the economic development and global warming have been focused on pursuing environmental sustainability and raising the efficiency of energy use around the world. In response to the global environmental issues, the Taiwan government formally established the National Council for Sustainable Development in 1997. Thereafter, the Taiwan sustainable development indicator (TSDI) system was developed using the pressure-state-response (PSR) framework for the purpose of showing the government's determination and effort for sustainable development. It should be noted that the energy strategies and policies for promoting renewable energy and energy saving have actively provided some environmental and financial/economic incentives in the past decade. A composite analysis of three energy sustainability indicators (i.e., CO_2 emissions per capita, energy intensity and renewable energy production) showed that Taiwan has experienced a positive progress towards energy sustainability during the period of 2000–2008.

On June 12, 2009, the Renewable Energy Development Act, which was aimed at promoting the use of renewable energy, boosting energy diversification, and helping reduce GHG emissions, was passed by the Legislature Yuan, Taiwan's law-making body. The Act was intended for attaining definite goals of cutting annual emission of CO_2 to the levels of the year 2008 during the period of 2016–2020, and curtailing annual emission of CO_2 to the levels of the year 2000 in 2025. It is undoubtedly anticipated that the energy sustainability is accessible, making Taiwan a model nation of sustainable development in the near future. On the other hand, the energy indicators are very useful for monitoring progress towards sustainable development at a national level. It is thus prospective that the energy sustainability indicators such as renewable energy share in energy supply and electricity generation should be incorporated into the current TSDI system in line with the goals of the national development in the energy and environmental domains.

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